An Iterative Receiver for WCDMA Systems with MIMO Transmissions and Hierarchical Constellations

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ABSTRACT

In this paper we consider the use of M-QAM hierachical constellations (Quadrature Amplitude Modulation) and MIMO (multiple input multiple output) for the transmission of multicast and broadcast services in the downlink connection of a WCDMA (Wideband Code Division Multiple Access) system. The objective is to increase the efficiency of the transmission by splitting the information in classes with different importance and mapping the bit streams of these classes to more or less protected positions of the modulation symbols. With this strategy, the most important information streams can be received by all users while the less relevant information will only be extracted by users with good propagation conditions. Due to the more demanding channel estimation requirements and the higher sensitivity to interference resulting from the usage of several antennas and hierarchical constellations, an enhanced receiver based on the turbo concept is developed and evaluated. It is shown that high transmission bit rates can be achieved even in high delay spread environments.

Keywords –WCDMA, MIMO, iterative decoding, hierarchical constellations.

I. INTRODUCTION

In a Wireless Communication Network it is often necessary to transmit the same information to all the users (broadcast transmission) or to a selected group of users (multicast transmission). Depending on the propagation conditions, some receivers will have better signal to noise ratios (SNR) than others and thus higher capacities. Cover [1] showed that in broadcast transmissions it is possible to exchange some of the capacity of the good communication links to the poor ones and the tradeoff can be worthwhile. A simple method to improve the efficiency of the network is to employ hierarchical non-uniform signal constellations which are able to provide unequal bit error protection. Using this approach, a given user can attempt to demodulate only the more protected bits or also the bits that carry the additional information, depending on the propagation conditions. A possible application of these techniques is in the transmission of coded voice or video signals. Several papers have studied the use of non-uniform constellations for this purpose [1]-[3]. Non-uniform 16-QAM and 64-QAM constellations have already been incorporated in the DVB-T (Digital Video Broadcasting - Terrestrial) standard [4]. In this paper we consider the use of 16-QAM and 64-QAM hierachical constellations for the transmission of broadcast and multicast services in WCDMA systems. For 16-QAM two classes of bits are used while for 64-QAM there are three classes of bits available.

Multiple-input multiple-output (MIMO) channels have recently emerged as a key technology in modern digital communication to provide substantial capacity increments [5][6]. The idea behind MIMO is to employ several spatially distributed antenna elements, both in the transmitter and in the receiver, so that, in a richly scattering environment, all the received signals can be processed in some way by the receiver that either allows an increase of the total bit rate or an improvement in the bit error rate (BER). In MIMO systems the channel estimation plays a crucial role since the performance of the spatial signal processing in the MIMO receiver depends on the accuracy of the channel estimates and thus any existing errors will have a significant negative impact. In this paper we consider the transmission of pilot channels orthogonal to the data channels, similarly to what is done in the downlink connection of UMTS (Universal Mobile Telecommunications Systems) where one of the orthogonal variable spreading factor codes (OVSF) is reserved for the transmission of the CPICH (Common Pilot Channel) [7]. In the case of MIMO, the pilot channels should also be orthogonal between the transmitting antennas. However, in WCDMA environments the channels are frequency selective and thus the orthogonality between the pilot sequences is destroyed, which can deteriorate the quality of the channel estimation process.

Since M-QAM hierarchical constellations are more sensitive to interference, to support their use in WCDMA MIMO transmissions it is necessary to develop adequate receivers with affordable complexities. An optimal receiver should be able to jointly perform channel estimation, MIMO channel equalization and decoding but the enormous complexity required to implement such a receiver makes it impractical. The alternative is to use a sub-optimal receiver scheme with the different processing steps performed separately. In the case of a system employing turbo-codes, due to the decoding being an iterative process, it is possible to incorporate some of the other blocks inside the iterative loop. This type of receivers for MIMO systems has started to capture considerable research interest in the last years. In [8] MIMO systems with pilot embedding transmissions were studied, where the receiver includes the channel estimator block inside the turbo decoder loop for improving the channel estimates in each iteration. In

[9] a space–time turbo equalizer for frequency-selective MIMO channels based on the MMSE decoder and which included channel estimation inside the iterative loop was described. Here the same concept is employed to develop an iterative receiver for WCDMA MIMO systems. This iterative receiver can employ an MMSE equalizer, a RAKE with interference cancellation (an extension of the turbo MPIC [10] – multipath interference canceller) or a mixture of these.

The structure of the paper is as follows. Section II gives a brief introduction about the design of non-uniform constellations and describes the modifications necessary in the transmitter structure of a WCDMA system to incorporate the hierarchical constellations and MIMO. In Section III, the iterative receiver is presented and explained. Section IV shows some performance results using the proposed transmission scheme and Section V presents the conclusions of this study.

II. PROPOSED WCDMA DOWNLINK TRANSMISSION SCHEME

A. M-QAM hierachical Signal Constellations

Hierarchical constellations with non uniformly spaced symbols are constellations where the distances along the I or Q axis between adjacent symbols can be different depending on their position. These constellations are thus able to provide unequal bit error protection. As an example, a non-uniform 16-QAM constellation can be constructed from a main QPSK constellation where each symbol is in fact another QPSK constellation, as shown in Figure 1.

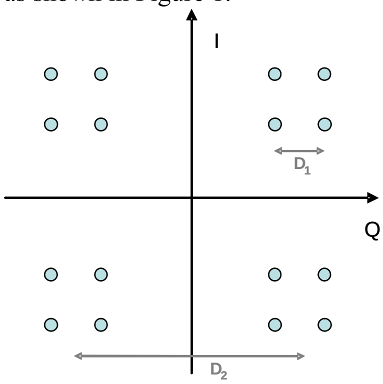

Figure 1. Non-uniform 16-QAM constellation.

The basic idea is that the constellation can be viewed as a 16-QAM constellation if the channel conditions are good enough or as a QPSK constellation otherwise. In the latter situation, the received bit rate is reduced to half. These constellations can be characterized by the parameter $k=D_1/D_2$ ($0<k\leq 0.5$), as shown in Figure 1. If $k=0.5$, the resulting constellation corresponds to a uniform 16-QAM. This approach can be naturally extended to any QAM constellation size M where the number of possible classes of bits with different error protection is $1/2\cdot\log_2 M$.

B. Transmitter Structure

Let us consider a WCDMA based downlink system employing hierarchical constellations and an $M_{tx}\times N_{rx}$ MIMO transmission. The proposed transmitter is an extension of the one employed in [10] with the addition of the multiple transmit antennas elements. The resulting chain is presented in Figure 2. In this scheme, there are also m parallel chains for m input bit streams which are independently turbo encoded (using the 3GPP rate 1/3 turbo code [11]) and to which, rate matching is performed (usually puncturing) for achieving the desired transmitted bit rates. Each stream is segmented into P physical channels (each physical channel is be spreaded by a different OVSF code which are then individually interleaved. The physical channels of the m processing chains are then mapped into the constellation symbols in the modulation mappers according to the importance attributed to each chain. The modulated symbols are spreaded, scrambled and the P symbol sequences are then summed. The resulting stream is then split into several smaller streams, pilot channels are added (one for each antenna) and then they are transmitted simultaneously by the M_{tx} multiple antennas. Note that in the proposed scheme the coding is not performed independently for each different antenna. Instead each data sequence is encoded and divided equally among the transmitting antennas by the Serial to Parallel block. The objective is to try to obtain some diversity for the same encoded block.

III. ITERATIVE RECEIVER

The structure of the proposed iterative receiver is shown in Figure 3. For the operation of the receiver it is assumed that all the parallel physical channels present in the transmitted signal carry information for that receiver or at least it has knowledge about them. The channel estimator block uses the transmitted pilot symbols for obtaining channel estimates. These estimates are then used for performing the demultiplexing of the simultaneous transmitted streams. This can be accomplished with either a MMSE equalizer or a RAKE with an interference canceller (IC).. The IC employed is based on the turbo MPIC [10] with the difference that in this case it has to cancel the interference of the multipath replicas and also of all the simultaneous transmitting antennas. The P demultiplexed symbol sequences then go into the succession of processing blocks that perform the inverse operations of the transmitter. One of the blocks is the demodulator, which computes the likelihood probabilities of the received coded bits to be used by the turbo decoders. Each turbo decoder has two outputs. One is the estimated information sequence and the other is the sequence of log-likelihood ratio (LLR) estimates of the code symbols. The MAP algorithm can used in the component decoders inside the turbo decoder block [12][13]. These LLR's are passed through the Decision Device which outputs either soft-decision or hard decision estimates of the code symbols. These estimates enter the Transmitted Signal Rebuilder which performs the same operations of the transmitter. The reconstructed signals then go into the channel estimator which uses the estimated transmitted symbols as pilots for a refinement of the channel estimates. In the case of using an IC, the transmitted signals estimates are also used for subtracting estimated multipath and inter-antenna interference from the signals fed to each finger of the RAKE.

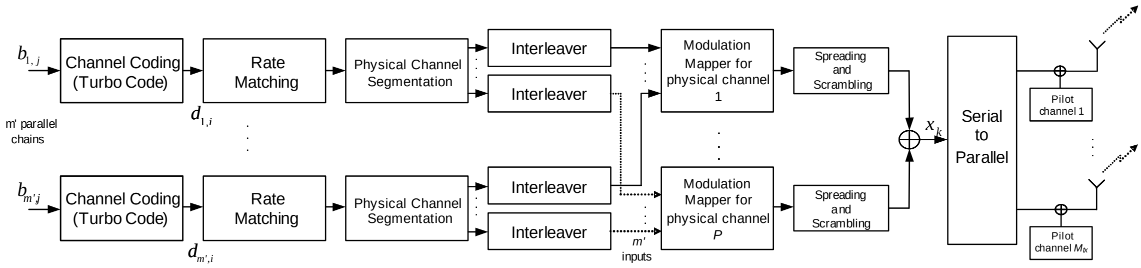

Figure 2. WCDMA downlink transmitter chain for a spatial multiplexing MIMO transmission, using hierarchical constellations

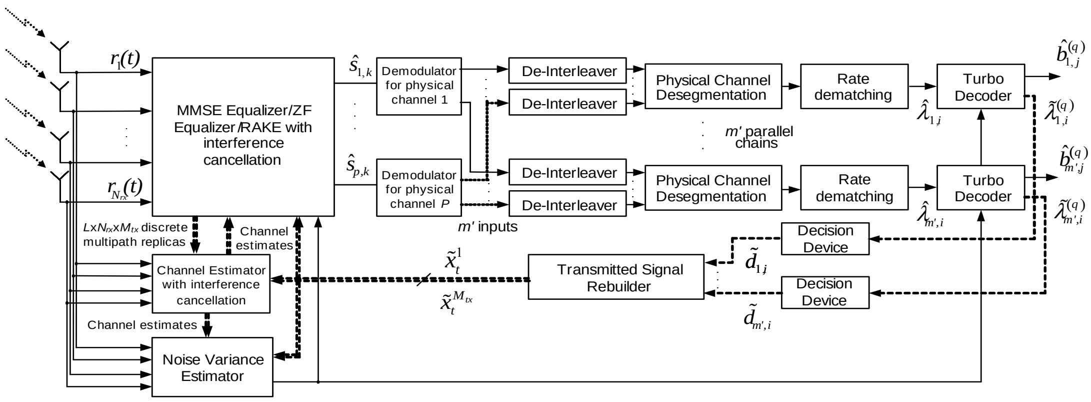

Figure 3. Iterative receiver structure with enhanced channel estimation.

In this case the transmitted sequences go through a channel emulator which generates estimates for all the discrete paths between the multiple transmit and receive antennas multiplied by the respective estimated channel coefficients. The interference subtracted from the signals provided to each RAKE finger is then composed by the sum of all paths coming from all transmitting antennas and arriving at the corresponding receiving antenna excluding the path that is going to be extracted by that finger. The interference signals can be weighted before the subtraction in the Interference Canceller, as was done in [10]. This allows subtracting weaker interference signals in the first iterations since the confidence in the estimated transmitted signal is lower. The IC is also applied in the channel estimation block for further improving the estimates, since the multipath and inter-antenna interference might also degrade the channel estimator performance. The noise estimator block estimates the noise variance required by the MMSE and also by the turbo-decoder.

In the proposed receiver it is possible to perform some of the iterations using one spatial demultiplex technique, like the MMSE decoder, and the others using a different one, like the RAKE with interference cancellation. The idea is to reduce the complexity of the receiver since the MMSE equalizer is more complex than a RAKE with IC. The description of the MMSE equalizer for MIMO WCDMA systems employed in this study is presented in [14].

IV. NUMERICAL RESULTS

As a first evaluation of the capabilities of the iterative scheme, simulations were run for comparing the performance of the iterative receiver (using an MMSE equalizer) against a non iterative. A pilot channel is transmitted in parallel with the data channels in each antenna with 10% of the total transmitted power by that antenna. The results are shown in Figure 4 which corresponds to a 2x2 MIMO system with SF=2, P=1, R=1/2 and uniform 64-QAM constellation (k_1=k_2=0.5) in a 2 taps Rayleigh fading channel. In the legend of the graph and of all the ones that will be presented next, the following abbreviation is employed: *N1*turbo/*N2*DEC1/*N3*DEC2/… which corresponds to the sequence of equalization methods in each receiver iteration and the number of turbo decoding iterations. *N1* is the number of turbo decoding iteration per receiver iteration, *N2* is the number of total receiver iterations that employed DEC1 decoding method, *N3* is the total number of receiver iterations that employed DEC2 decoding method, and so on. The decoding methods, DEC1, DEC2,…, can be either MMSE or IC (RAKE with interference cancellation).

In the results presented in Figure 4 it is visible that the most protected bit, bit 1, has a performance very close to the ideal estimation case independently of using the iterative scheme or not. As for the other two bit types, the performance obtained when using a non iterative receiver is severely degraded compared with the perfect estimation curve. This degradation is caused by a poor channel estimation due to the presence of interference in the pilot channels generated by the arriving delayed multipath signal replicas (data plus pilot). With the use of the iterative scheme the interference is suppressed and substantial improvements can be obtained for bit 2 and 3.

The proposed iterative receiver allows the use of different equalization methods for each iteration. To compare different receiving strategies, several simulations were performed. Figure 5 and Figure 6 present the results of the most protected and least protected bit streams, respectively, in the case of a 2x2 MIMO system with *SF*=4, *P*=2, *R*=1/2, uniform 16-QAM constellation (k=0.5) and a 2 taps Rayleigh fading environment.

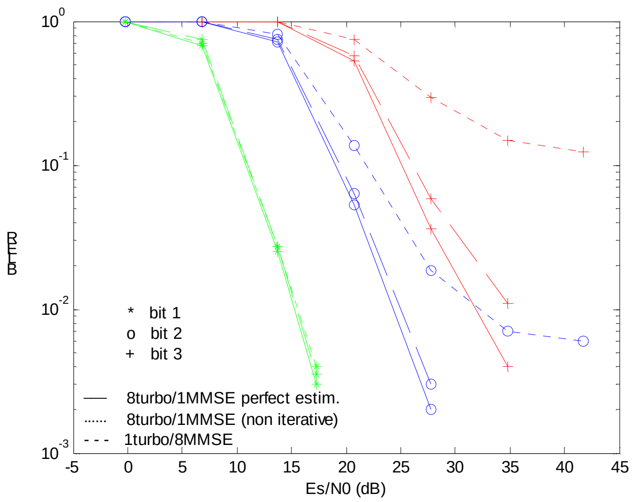

Figure 4. Comparison between non iterative estimation and an iterative estimation scheme for a 2x2 MIMO transmission (*SF*=2, *R*=1/2, uniform 64-QAM, 2 Rayleigh taps environment, *v*=20km/h).

In the graphs, it is visible, specially for the least protected bit streams, that the best performances are attained with the two schemes where the first iterations employ an MMSE and the others use a RAKE with IC. This type of approach takes advantage of the qualities of both methods and can obtain performance improvements over schemes that only use one of the decoding methods in all iterations. This is due to the fact that the information fedback by the receiver in each iteration affects only the MMSE equalizer through the improvement of the channel estimates and thus, after a certain number of iterations, the use of the MMSE may not be able to provide any more substantial improvements. However, in the case of the RAKE with IC, the feedback information also allows the subtraction of better estimates of interference and thus, there is always the possibility of improving the performance with a high number of iterations even if the channel estimates are already accurate. When only the RAKE with IC is used, it is visible in the figures that the performance is poor since the receiver is not able to achieve good estimates of the interference to be removed. By using a MMSE in the first iterations, it is possible to obtain good estimates of the transmitted signal and channel coefficients and subtract almost all the interference from the RAKE fingers in the last iterations. If the order of the decoding method used in the iterations is inverted, like using a RAKE with IC in the first three iterations and an MMSE in the fourth iteration, then it is visible from the results that the performance gets substantially worse. In this case, the use of the RAKE with IC initially, results in worse estimates of the transmitted signals and therefore of the channel coefficients. Consequently, when the MMSE is used in the last iteration, the channel estimates are poor and the performance will not be as good as in the other combined schemes (high BLER floors are visible in the figures).

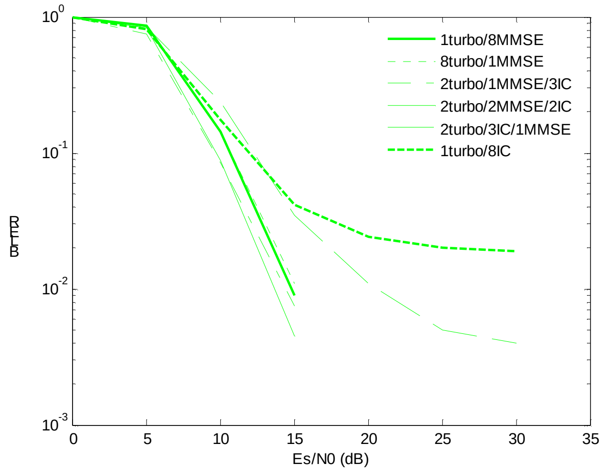

Figure 5. Performance of several MMSE/IC based iterative receivers for a 2x2 MIMO transmission (*SF*=4, *P=2*, *R*=1/2, uniform 16-QAM, 2 Rayleigh taps environment, *v*=20km/h). Most protected bit streams.

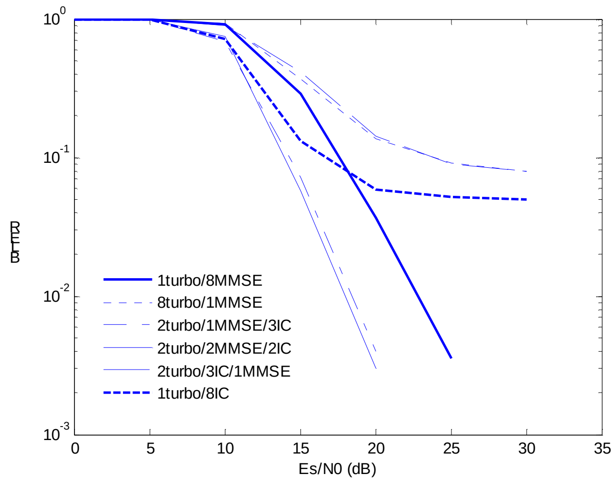

Figure 6. Performance of several MMSE/IC based iterative receivers for a 2x2 MIMO transmission (*SF*=4, *P=2*, *R*=1/2, uniform 16-QAM, 2 Rayleigh taps environment, *v*=20km/h). Least protected bit streams.

In Figure 7 the throughput performance is plotted for several transmission schemes as a function of the average received E_b/N_0 per receiving antenna, in a Vehicular A environment (v=120km/h), which has a high delay spread [15]. Assuming that these are broadcast transmissions, the blocks in error can be simply discarded, and the throughput can be defined as

$$\eta = R_b\left(1 - BLER\right) \qquad (1)$$

where R_b is the total information bit rate. The three cases shown in Figure 7 consider the same spreading factor, code rate, modulation and number of physical channels per transmission antenna. The differences lie on the number of transmit/receive antennas. This figure also shows the transmitted information rate for each scheme. The receiver used employs two MMSE iterations followed by two iterations with a RAKE with IC. Two turbo decoding iterations are performed in each receiver iteration. Comparing the case of one antenna at the transmitter and receiver (SISO - single input single output) with the case of one antenna at the transmitter and two at the receiver (SIMO - single input multiple output), we see that the maximum attainable throughput of 7.2Mbps, which is the same for both cases, is achieved (approximately) for a lower E_b/N_0 by the SIMO scheme. Therefore, the simple addition of antennas at the receiver can result in substantial performance improvements due to the increase on the resulting diversity. If an antenna is also added at the transmitter side (MIMO transmission), it is shown in the graph that, although the throughput becomes worse compared with the SIMO case for low E_b/N_0, it achieves a much higher maximum throughput. Although the iterative receiver developed in this paper is based on the presence of a turbo code, the approach can be directly applied to other channel codes, as long as the channel decoder can be implemented as a soft input soft output block.

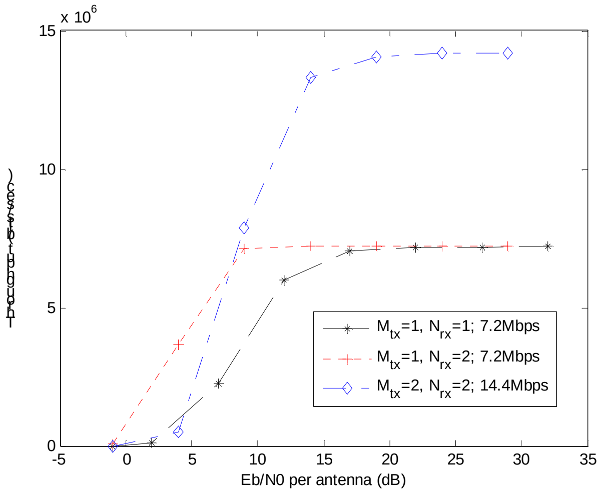

Figure 7. Comparison of throughput for several transmission schemes (*SF*=8, *P*=5, *R*=9/12, uniform 16-QAM, Vehicular A environment, *v*=120km/h).

V. CONCLUSIONS

In this paper an iterative receiver was proposed for a MIMO WCDMA system that employs hierarchical constellation. It was verified that with the proposed scheme it is possible to remove the interference from the channel estimation process and improve the performance substantially. It was also studied the possibility of using different MIMO decoding methods (MMSE, ZF and RAKE with IC) in different receiver iterations mainly to reduce the overall complexity. It was observed that by using an MMSE equalizer in the first iterations and a RAKE with IC in the others it is possible to obtain better performances than using only the MMSE or the RAKE with IC in all the iterations. It was shown that with the proposed receiver, high transmission bit rates can be achieved even in high delay spread environments.

IV. ACKNOWLEDGEMENTS

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V. REFERENCES

[1] T. Cover, “Broadcast channels”, IEEE Trans. On Inform. Theory, vol.IT-18, pp.2-14, January 1972.

[2] K. Ramchandran, A. Ortega, K. M. Uz, and M. Vetterli, “Multiresolution broadcast for digital HDTV using joint source/channel coding”, IEEE J. Select. Areas Commun., vol. 11, January 1993.

[3] Lee-Fang Wei, “Coded modulation with unequal error protection”, IEEE Trans. on Comm., vol. 41, pp. 1439–1449, Oct. 1993.

[4] ‘Digital video broadcasting (DVB) framing structure, channel coding and modulation for digital terrestrial television (DVB-T)’, Mar. 1997. ETSI, European Telecommunication Standard ETS 300 744.

[5] E. Telatar, “Capacity of multiantenna Gaussian channels,” *AT&T Bell Laboratories*, *Technical Memorandum*, June 1995.

[6] G. J. Foschini and M. J. Gans, “On limits of wireless communications in a fading environment when using multiple antennas,” *Wireless Pers.Commun.*, vol. 6, pp. 311–335, Mar. 1998.

[7] 3GPP, 25.211-v6.3.0, ‘Physical channels and mapping of transport channels onto physical channels (FDD)’, Dec. 2004.

[8] H. Zhu, B. F.-Boroujeny, C. Schlegel, “Pilot Embedding for Joint Channel Estimation and Data Detection in MIMO Communication Systems”, *IEEE Communication Letters,* vol. 7, no. 1, Jan. 2003.

[9] T.Abe and T. Matsumoto,” Space–Time Turbo Equalization in Frequency-Selective MIMO Channels ”, *IEEE Trans. On Vehicular Technology*, vol. 52, no. 3, May 2003.

[10] N. Souto; J. C. Silva; F. Cercas; R. Dinis, “Iterative Turbo Multipath Interference Cancellation for WCDMA Systems with Non-Uniform Modulations”, Proc. IEEE Vehicular Technology Conf. - VTC2005-Spring, Stockholm, Sweden, May-June, 2005.

[11] 3GPP, 25.212-v6.2.0, ‘Multiplexing and Channel Coding (FDD)’.

[12] L. R. Bahl, J. Cocke, F. Jeinek, and J.Raviv. “Optimal decoding of linear codes for minimizing symbol error rate.” *IEEE Trans. Inform. Theory*, vol. IT-20, pp. 248-287, March 1974.

[13] S. Benedetto, G. Montorsi, “A Soft-Input Soft-Output APP Module for Iterative Decoding of Concatenated Codes”, *IEEE Comm. Letters*, vol.1, no.1, pp.22-24, January 1997.

[14] J. Silva, N. Souto, F. Cercas, R. Dinis, A. Correia, A. Rodrigues, “Equalization Based Receivers for Wideband MIMO/BLAST Systems”, Proc. IEEE International Symp. on Wireless Personal Multimedia Communications WPMC 2005, 17-22 September, Aalborg, Denmark.

[15] ‘Selection procedures for the choice of radio transmission technologies of UMTS’, ETSI, TR 101 112 v3.2.0, Sophia Antipolis, France, 1998.